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POST-FIRE MECHANICAL PROPERTIES OF COLD-FORMED STEELS

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INTRODUCTION

Cold-formed steel members are becoming increasingly popular in the construction industry due to their superior strength to weight ratio and ease of fabrication as opposed to hot-rolled steel members. They are commonly used as load bearing studs and joists in light gauge steel frame (LSF) walls and floors lined with plasterboards. Inevitably, they can be exposed to fire events. The temperature rise in cold-formed steel studs and joists under a fire event depends on many parameters such as the fire time-temperature curve, duration of the fire and LSF wall configurations (details of plasterboard linings, insulations and their layouts and stud sections). Recent researches have provided a good understanding of the mechanical properties of cold-formed steels [1-5] and the behaviour of LSF walls [6-10] and floors [11] at elevated temperatures. Upon cooling from elevated temperatures, the plasterboards which protected the cold-formed steel studs and joists can be easily removed from the steel frames to see the damage caused by elevated temperatures. The structural engineer then has to decide if the strength of the light gauge frame is still adequate for future use by using new plasterboard linings.
The behaviour of structural steel frames after fire events is investigated in [12,13]. Integrity testing procedures have been developed in this study to verify the adequacy of steel members after being exposed to fire. This includes visual observation, non-destructive testing, destructive testing and rectification. Visual observation is used to identify the location of maximum intensity and to estimate temperatures reached during the fire (concrete colour changes, melting glass/plastic etc). The most common form of non-destructive testing used in post-fire evaluation is the surface hardness test. Destructive testing involves the removal of a specimen from damaged steel structures and the evaluation of physical properties, residual stresses and grain structures. Rectification of the structure involves compiling the results of the integrity testing and evaluating the next stage which includes replace, repair or strengthen the structural members. In the event of a fire, the extreme temperature variations can change the sectional and member load bearing capacities of steel members. The main reason for this is the change in post-fire mechanical properties (yield strength, elastic modulus, ultimate strength and ductility) of steel sections after being exposed to fire events. Currently the design standards contain no information on the mechanical properties of steels after being exposed to elevated temperatures. Qiang et al. [16] investigated the post-fire mechanical properties of high strength structural steels (S460 and S690) and proposed suitable predictive equations. However, the behaviour of cold-formed steels after fire events has not been investigated yet. Outinen and Makelainen [1] conducted research on various structural steels and reported the post-fire mechanical properties of only the S355 grade cold-formed steel. There are also no design guidelines in [14,15] for assessing fire exposed cold-formed steel members. As a result of this limited knowledge on post-fire behaviour of cold-formed steel members, over conservative decisions can be made when evaluating fire exposed cold-formed steel section and member capacities. Improved knowledge of these capacities would help engineers make the right decisions.
Hence this paper investigates the mechanical properties of cold-formed steels after being exposed to elevated temperatures and proposes new equations to predict post-fire mechanical properties. Information gained will assist engineers in determining the mechanical properties and assessing the axial and bending capacities of fire exposed cold-formed steel sections prone to various buckling modes and may also assist in further development of the Australian/New Zealand Standards with regards to post-fire cold-formed steel structural assessments.

1 EXPERIMENTAL STUDY

An experimental study was undertaken at the Queensland University of Technology to determine the post-fire mechanical properties of cold-formed steels after a fire event. Tensile coupon tests were conducted on three different steel grades and thicknesses to obtain their stress-strain curves and relevant mechanical properties (yield stress, Young's modulus, ultimate strength and ductility). In this experimental study, cold-formed steel specimens were heated up to pre-determined temperatures and then allowed to cool down at ambient temperature. A tensile load was applied thereafter at a constant rate as strain controlled until failure. Tensile coupon tests were conducted to determine the mechanical properties of G300-1.00 mm, G500-1.15 mm and G550-0.95 mm steels at ambient and pre-selected exposed temperatures up to 800^{o}C. Test specimens were cut in the longitudinal direction of cold-formed steel sheets. The shapes and sizes of specimens were in accordance with AS 1391 [17].

The electric furnace shown in *Fig. 1(a)* was used in this experimental study to achieve the desired elevated temperature. The thermocouple located inside the furnace gave the air temperature of the furnace on the display. Two additional thermocouples were placed inside the furnace to measure the temperature independently. Ten different temperatures were selected in this study: 20, 300, 400, 500, 550, 600, 650, 700, 750 and 800 ^{o}C. The cold-formed steel becomes very soft at temperatures above 800^{o}C and hence temperatures higher than 800^{o}C were not considered in the current study. Initially, the specimens were placed inside the furnace using paper clips as props. The furnace temperature was then carefully increased at a heating rate of 10 – 20 ^{o}C/min without any over-shooting of the target temperature. The specimens were then removed from the furnace and placed on a tray to air cool at its own rate. They were then treated with diluted hydrochloric acid to remove any oxide and coatings that formed on the surface of the steel. Thereafter the strain gauges were attached to measure strains during the tensile coupon tests.

Instron machine was used for the tensile coupon tests. A tensile load was applied at a constant strain rate until failure. The displacement rate used was 1 mm/min, which satisfied the requirement of AS 1391 [17]. *Fig. 1(b)* shows the details of the tensile test set-up. Tensile specimen was connected to the top and bottom grips, which were accurately aligned with each other. The bottom end was fixed while the top end was free to move upwards. The applied load was measured using a load cell of 50 kN attached to the Instron testing machine. The lab view system was used as the data logger to record the load, displacement and strain gauge measurements.

a) b) c)

Fig. 1. a) Furnace and test specimens after being exposed to an elevated temperature of 800 ^{o}C; b) Test set-up; c) Failure modes of G500-1.15 mm test specimens for different exposed temperatures

2 RESULTS AND DISCUSSIONS

2.1 Visual observations

Fig. 1(a) shows the test specimens after being exposed to different elevated temperatures. The cold-formed steel specimens deteriorated quite steadily up to 500^{o}C. After this temperature, the effect of heat caused visible damage to steel specimens. For exposed temperatures above 600^{o}C, flaking was observed in the form of oxide for high grade (G500 and G550) steels. This oxide would be a useful indicator for approximate fire intensity in a practical scenario. The G300 steel specimen became quite abrasive around the edges from approximately 500^{o}C onwards and did not show any signs of oxide formation or flaking. As the steel became soft with increasing temperatures (700^{o}C and above), it was important that no deformations occurred while removing the specimen from the furnace. *Fig. 1(c)* shows the failed steel specimens after the tests.

2.2 Elastic modulus

Fig. 2(a) shows the comparison of stress-strain curves for G500-1.15 mm cold-formed steels after being exposed to temperatures in the range of 20 to 800^{o}C. Elastic modulus was calculated from the initial slope of the stress–strain curve. The elastic modulus reduction factor for exposed temperatures was then calculated as the ratio of the elastic modulus after being exposed to an elevated temperature (T) E_T to that at ambient temperature E_{20} given in *Table 1*. The modulus of elasticity remained relatively unchanged up to 700°C for low grade steel (*Fig. 2(b)*). For low grade steel 4% reduction in elastic modulus was observed at 800^{o}C. The elastic modulus of the high grade steel specimens decreased more than the low grade steel specimens when exposed to elevated temperatures. This is similar to the outcome obtained from the study of Qiang et al. [16]. There was almost no change in the elastic modulus of high grade steel for temperatures up to 400°C. It then steadily decreased by 10 - 15% as the exposed temperature increased to 800°C.

2.3 Yield strength

The 0.2% proof stress was determined for all the steel grades. In addition, the stresses at 0.5%, 1.5% and 2.0% strain levels were also determined from the intersection of stress–strain curve and a non-proportional vertical line at the specified strain values. The yield strength reduction factors for exposed temperatures were calculated as the ratio of yield strength after being exposed to an elevated temperature (T), $f_{y,T}$, to that at ambient temperature, $f_{y,20}$, given in *Table 1*. It was observed that the yield strength reduction factors based on 0.5%, 1.5% and 2% total strain are closer to those based on 0.2% proof stress, for both low and high grade steels.

Fig. 2(c) demonstrates that the yield strength reduction characteristics of low (G300) and high grade steels (G500 and G550) are different. It appears that the yield strengths of high grade steels do not decrease much up to 300^{o}C. High grade steels lose their yield strength more rapidly than the low grade steels in the exposed temperature range 500 - 600^{o}C with a strength reduction of approximately 50%. The yield strength reduced gradually after this temperature up to 800^{o}C. Unlike high grade steels, the yield strength of low grade steels reduced even in 300 °C showing an initial strength decrease of 8%. The low grade steel yield strength decreased by 30% at 800^{o}C compared to the value at ambient temperature.

2.4 Ultimate strength

The ultimate strength reduction factors were calculated based on the ratio of ultimate strength after being exposed to an elevated temperature (T) $f_{u,T}$ to that at ambient temperature $f_{u,20}$ given in *Table 1*. The reduction in ultimate strength follows a similar trend to that of the reduction in yield strength. However, the reduction in ultimate strength was less than the reduction in yield strength for both low and high grade steels as shown in *Figs. 2(c) and (d).*

2.5 Ductility

Ductility of steel is defined based on the level of deformation that steel can undergo plastically before fracture. Low grade steel (G300) shows higher ductility than that of high grade steel (G500 and G550) at ambient temperature. This can be attributed to the comparatively high strain hardening caused by cold working in the case of high grade steel. Typical failure modes for low and high grade cold-formed steels for different exposed temperatures are shown in *Fig. 1(c)*. Up to 500^{o}C, high grade steels showed less ductile failures (brittle with no necking) and thereafter their failures became more ductile. Brittle failure was not seen in G300 steel, which showed ductile behaviour at ambient and exposed temperatures. The observations in this study indicate that lack of ductility is not a concern for cold-formed steels considered here for exposed temperatures up to 800^{o}C.

Table 1. Post-fire mechanical properties

T (^{o}C)	elastic modulus (MPa)			yield strength (0.2%) (MPa)			ultimate strength (MPa)		
	G300-1.00	G500-1.15	G550-0.95	G300-1.00	G500-1.15	G550-0.95	G300-1.00	G500-1.15	G550-0.95
20	209053	227096	231575	351.5	663.9	664.4	366.2	668.3	664.4
				reduction factors					
300	1.006	0.995	1.000	0.922	0.990	1.010	0.984	1.001	1.016
400	1.014	0.991	0.993	0.921	0.981	0.984	0.976	0.980	0.990
500	1.002	0.987	0.979	0.872	0.917	0.833	0.950	0.921	0.845
550	0.991	0.965	0.907	0.855	0.616	0.466	0.937	0.685	0.530
600	1.008	0.953	0.906	0.879	0.431	0.452	0.923	0.526	0.516
650	0.993	0.917	0.909	0.845	0.351	0.426	0.917	0.480	0.514
700	0.991	0.912	-	0.723	0.394	-	0.849	0.485	-
750	0.984	0.895	0.888	0.680	0.372	0.392	0.866	0.487	0.489
800	0.964	0.896	0.854	-	0.395	0.364	-	0.490	0.479

3 PREDICTIVE EQUATIONS FOR POST-FIRE MECHANICAL PROPERTIES

3.1 Elastic modulus

With the availability of accurate elastic modulus reduction factors of different steel grades (G300, G500, and G550) and thicknesses (0.95 - 1.15 mm), it was considered important to develop predictive equations that are suitable for commonly used cold-formed steels in Australia. Qiang et al. [16] developed predictive equations for the elastic modulus reduction factors as a function of exposed temperature for high strength structural steels. However, their equations did not accurately predict the elastic modulus reduction factors for cold-formed steels and hence new empirical equations were developed. Test results from this study showed that the steel grade has some influence on the elastic modulus reduction factors. Hence two separate sets of predictive equations were developed for low and high grade steels. There are two main regions in which the elastic modulus reduction factors vary linearly: 700 - 800^{o}C for low grade steels and 400 - 800^{o}C for high grade steels. Hence linear equations were developed for the two identified temperature regions to predict the elastic modulus reduction factors for exposed temperatures of low (*Eq. (1b)*) and high grade steels (*Eq. (2b)*). *Fig. 2(b)* shows that the test results from this study agree well with the proposed equations.

Low Grade $RF = 1$ *for* $20\,^{o}C \le T \le 700\,^{o}C$ (1a)

Low Grade $RF = 1.28 - 0.0004\,T$ *for* $700\,^{o}C < T \le 800\,^{o}C$ (1b)

High Grade $RF = 1$ *for* $20\,^{o}C \le T \le 400\,^{o}C$ (2a)

High Grade $RF = 1.15 - 0.000375\,T$ *for* $400\,^{o}C < T \le 800\,^{o}C$ (2b)

3.2 Yield strength

Comparison of the yield strength results obtained from this research and the predicted values from Qiang et al's [16] equations showed that they were unable to predict the yield strength reduction factors of cold-formed steels for exposed temperatures accurately. Therefore new predictive equations were proposed as follows based on the 0.2% proof stress method. The yield strength of low grade steels steadily decreased as the specimens were exposed to temperatures up to 650°C. After this temperature, the yield strength considerably decreased linearly with respect to exposed temperatures. *Eqs. (3a) and (3b)* present the proposed equations for the yield strength (0.2%)

reduction factors of low grade steels (G300). Similarly a new set of equations was developed to determine the yield strength reduction factors of high grade steels (G500 and G550) by considering the test results obtained from this study. The reduction factors of high grade steels show three main regions after 300°C: two nonlinear regions (300 – 500 and 500 – 600°C) and one linear region (600 – 800°C). Three equations were therefore developed to represent them. *Eqs. (4a) to (4d)* present the proposed equations for the yield strength reduction factors of high grade steels. In *Fig. 2(c)*, the predictions from the proposed equations are compared with the test results from this research. As shown in the figure there is good agreement between the test results of this study and the proposed equations. Therefore it is recommended to use the proposed equations to determine the yield strength reduction factors of cold-formed steels for exposed temperatures.

Low Grade	$RF = 1.005 - 0.00024\,T$	for $20\,^oC \le T \le 650\,^oC$	(3a)
Low Grade	$RF = 2.02 - 0.0018\,T$	for $650\,^oC < T \le 800\,^oC$	(3b)
High Grade	$RF = 1$	for $20\,^oC \le T \le 300\,^oC$	(4a)
High Grade	$RF = -3.5 \times 10^{-6}\,T^2 + 2.15 \times 10^{-3}\,T + 0.67$	for $300\,^oC \le T \le 500\,^oC$	(4b)
High Grade	$RF = 3.8 \times 10^{-5}\,T^2 - 4.63 \times 10^{-2}\,T + 14.52$	for $500\,^oC \le T \le 600\,^oC$	(4c)
High Grade	$RF = 0.63 - 0.00035\,T$	for $600\,^oC < T \le 800\,^oC$	(4d)

3.3 Ultimate strength

Eqs. (5a) and (5b) and *Eqs. (6a) to (6d)* present the proposed equations for the ultimate strength reduction factors of cold-formed steels. The predictions from these equations are compared with the test results from this study in *Fig. 2(d)*. This figure shows that there is good agreement between the proposed equations and the test results. Therefore it is recommended to use the proposed equations to determine the ultimate strength reduction factors of cold-formed steels for exposed temperatures.

Low Grade	$RF = 1.002 - 0.000104\,T$	for $20\,^oC \le T \le 500\,^oC$	(5a)
Low Grade	$RF = 1.114 - 0.00033\,T$	for $500\,^oC < T \le 800\,^oC$	(5b)
High Grade	$RF = 1$	for $20\,^oC \le T \le 300\,^oC$	(6a)
High Grade	$RF = -2.5 \times 10^{-6}\,T^2 + 1.45 \times 10^{-3}\,T + 0.79$	for $300\,^oC \le T \le 500\,^oC$	(6b)
High Grade	$RF = 3.8 \times 10^{-5}\,T^2 - 4.57 \times 10^{-2}\,T + 14.24$	for $500\,^oC \le T \le 600\,^oC$	(6c)
High Grade	$RF = 0.56 - 0.0001\,T$	for $600\,^oC < T \le 800\,^oC$	(6d)

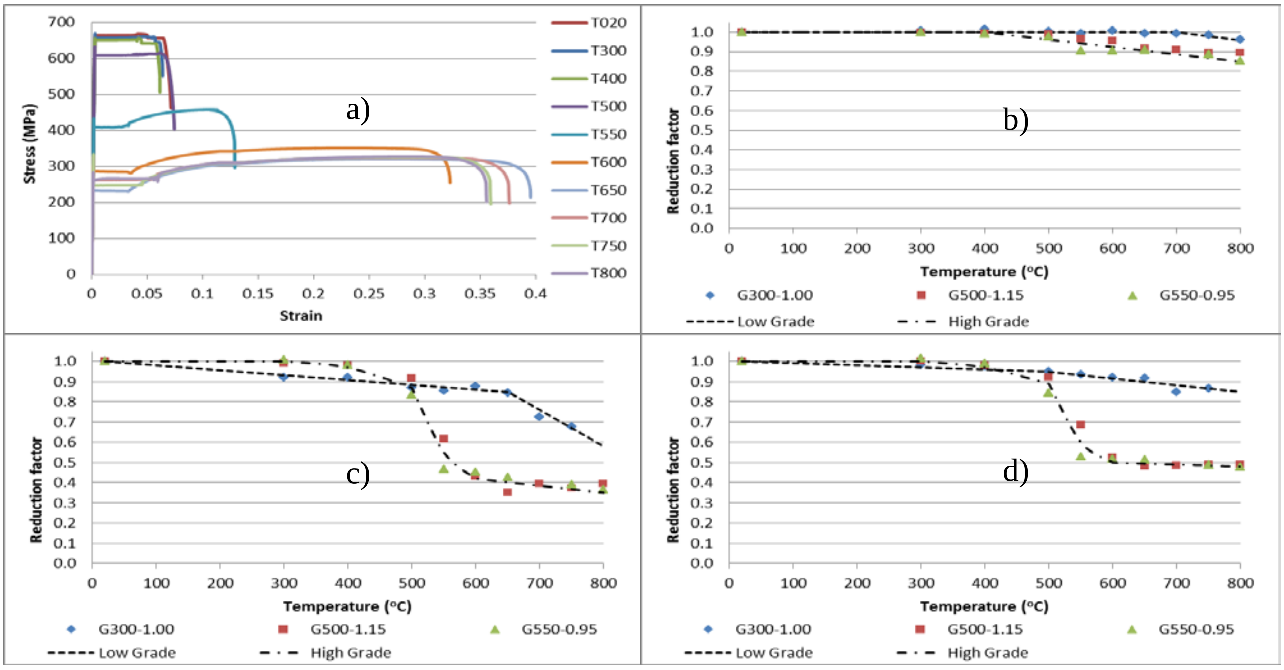

Fig. 2. a) Stress-strain curves of G500-1.15 steel for different exposed temperatures; b) Elastic modulus reduction factors versus exposed temperatures; c) Yield strength reduction factors versus exposed temperatures; d) Ultimate strength reduction factors versus exposed temperatures

4 SUMMARY

This paper has presented a detailed experimental study of the post-fire mechanical properties of cold-formed steels. The experimental study included tensile coupon tests conducted on G300-1.00, G500-1.15 and G550-0.95 mm cold-formed steels for an exposed temperature range of 20 - 800^{o}C. Test specimens were heated to various elevated temperatures before being allowed to cool back to ambient temperature. The stress-strain curves, yield and ultimate strengths and elastic modulus were determined from the tensile coupon tests. The results showed that the steel grade had an influence on the yield strength and elastic modulus of steel while there was no observable influence of steel thickness on the results. The reductions in yield strength and elastic modulus of low grade steel were found to be less than that of the high grade specimens. High grade steel was found to significantly lose its yield strength after being exposed to temperatures above 500°C. Neither the current design standards nor the proposals by other researchers provided reduction factors for the yield strength, ultimate strength and the elastic modulus of cold-formed steels for exposed temperatures. Therefore suitable predictive equations were developed for the mechanical properties of low and high grade cold-formed steels for exposed temperatures based on test results.

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